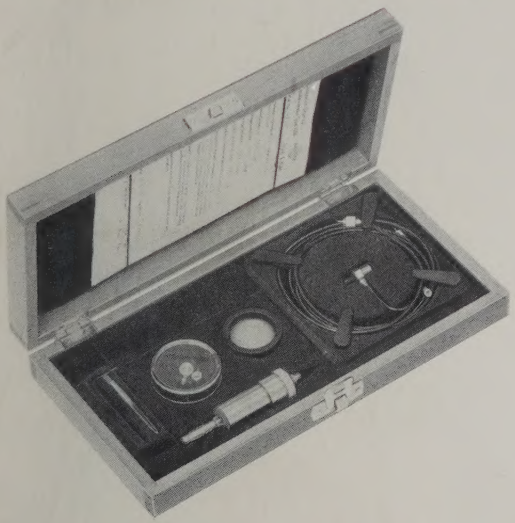
SER# 32226

4316/4356

INSTRUCTIONS AND APPLICATIONS

ACCELEROMETER SETS Type 4316
ACCELEROMETER PACKAGES Type 4356



The Miniature Accelerometer Type 4316 is designed especially with a view to vibration measurement on lightweight structures, where a heavy transducer would change the mode of vibration and thereby invalidate the results obtained. It will be found valuable in research projects involving thin plates and shells, such as aircraft skins, car bodies, component testing etc.

Accelerometers
Acoustic Standing Wave Apparatus
Artificial Ears
Artificial Voices
Audio Frequency Response Tracers
Audio Frequency Spectrometers
Audio Frequency Vacuum-Tube Voltmeters
Automatic A. F.Response and Spectrum Recorders
Automatic Vibration-Exciter Control Generators
Band-Pass Filter Sets
Beat Frequency Oscillators
Complex Modulus Apparatus
Condenser Microphones
Deviation Bridges
Distortion Measuring Bridges
Frequency Analyzers
Frequency Measuring Bridges
Hearing Aid Test Apparatus
Heterodyne Voltmeters
Level Recorders
Megohmmeters
Microphone Accessories
Microphone Amplifiers
Microphone Calibration Apparatus
Mobile Laboratories
Noise Generators
Noise Limit Indicators
Pistonphones
Polar Diagram Recorders
Preamplifiers
Precision Sound Level Meters
Recording Paper
Strain Gage Apparatus and Accessories
Surface Roughness Meters
Variable Frequency Rejection Filters
VHF-Converters
Vibration Pick-ups
Vibration Pick-up Preamplifiers
Wide Range Vacuum Tube Voltmeters

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Accelerometer Sets

Type 4316

Accelerometer Packages

Type 4356

NOVEMBER 1966

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0. Introduction

The accelerometer is an electromechanical transducer which produces at its output terminals an e.m.f. proportional to the acceleration to which the transducer is subjected. The output signal can be electronically processed and read on a meter or some other suitable indicating device.

The Brüel & Kjær accelerometers are small, light and of rugged construction, suitable for most vibration measurements, both in the laboratory and in field environments. Versatility in use has been a prime goal and special care has been taken to ensure a wide frequency range, high sensitivity and good temperature characteristics. Furthermore, these accelerometers have negligible mounting error and low sensitivity to severe environmental conditions, such as humidity, high temperature, corrosive atmospheres and magnetic fields.

The Miniature Accelerometer Type 4336 is designed especially with a view to vibration measurement on lightweight structures, where a heavy transducer would change the mode of vibration and thereby invalidate the results obtained. It will be found valuable in research projects involving thin plates and shells, such as aircraft skins, car bodies, component testing etc.

Measurements can be carried out as measurements of acceleration using one of the B & K preamplifiers or cathode followers, and as measurements of velocity or displacement employing integration networks.

For absolute measurements it is necessary to know the sensitivity of the vibration transducer employed. Each B & K accelerometer is supplied with individual calibration data and a frequency response curve, all taken as part of the production test procedure. The aim has been to supply the maximum amount of information on the calibration sheet to ensure a completely predictable performance of the accelerometers.

The Miniature Accelerometer has type number 4336 when on its own in the production and calibration stages. When it is sold it is accompanied by certain accessories such as connecting cable, mounting studs etc., and is available only as Accelerometer Set Type 4316 or as Accelerometer Package Type 4356. See section "What to Order" at the end of this book.

1. Description

Construction.
The Miniature Accelerometer Type 4336 is of the piezoelectric compression type with a construction indicated schematically in Fig. 1.1.

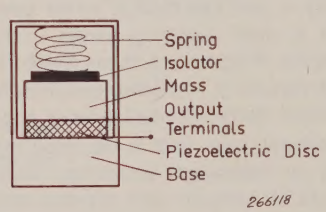


Fig. 1.1. Schematic drawing of a piezoelectric accelerometer.

The transducing element consists of a piezoelectric*) disc on which is resting a heavy mass. The mass is preloaded by a stiff spring and the whole assembly is mounted in a metal housing with a thick base. When the accelerometer is subjected to vibration, the mass will exert a variable force on the piezoelectric disc. This force is exactly proportional to the acceleration of the mass. Due to the piezoelectric effect a variable potential will be developed across the disc, which is proportional to the force and therefore to the acceleration of the mass. For frequencies much lower than the resonance frequency of the mass and the stiffness of the whole accelerometer system the acceleration of the mass will be virtually the same as the acceleration of the whole transducer, and the potential produced will therefore be proportional to the acceleration to which the transducer is subjected. This potential can be picked up from the output terminals of the accelerometer and used for determination of the vibration amplitude, waveform and frequency.
It has been the aim with the miniature accelerometer to make available a transducer of extremely low mass, which at the same time has the versatility of a general purpose accelerometer. High precision and stability coupled with a rugged construction make the accelerometer suitable for the most demanding applications both in the laboratory and in the field.

*) Lead Zirconium Titanate.

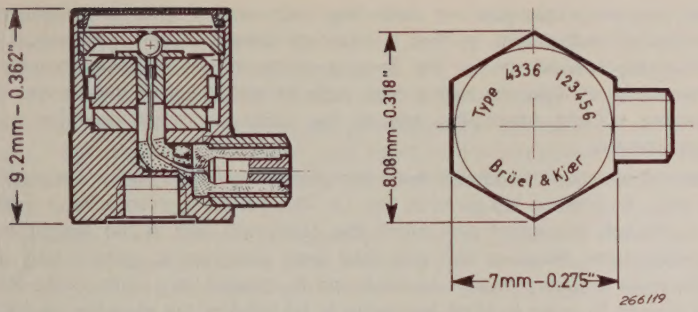


Fig. 1.2. Physical dimensions of the Miniature Accelerometer.

Physical Dimensions.

It is generally true that an accelerometer should be as light as possible in order not to influence the vibration of the specimen on which it is mounted. For measurements on heavy machinery etc. this causes no problem but for lighter structures, such as for example a thin metal plate, the transducer weight is important.

The resonance frequency of a vibrating single degree of freedom system is

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m_0}}$$

where m_0 is the effective lumped mass and k is the lumped stiffness restraining the mass.

It is easily seen that adding another mass, e.g. an accelerometer, will result in a change in resonance frequency according to the formula

$$\frac{f_1}{f_0} = \sqrt{\frac{m_0}{m_1 + m_0}}$$

where f_1 is the new resonance frequency and m_1 is the added mass.

Thus any mass added to a vibrating structure will influence the vibration to some extent, but provided the added mass is small the influence is often negligible. A 10 % increase in mass will reduce the resonance frequency by about 5 %.

The sensitivity of a piezoelectric accelerometer is directly proportional to the mass acting on the piezoelectric disc. This limits the extent to which the accelerometer weight may be reduced without loosing too much of the sensitivity. For many applications it is also important that any strain developed in the material on which the accelerometer is fixed is not transmitted to the piezoelectric element as this would show up in the output signal, indicating an acceleration which actually is not present. It is therefore necessary to make the accelerometer base thick, in order to isolate the piezoelectric disc from such strain. The requirements to high sensitivity, low strain sensitivity and good

high frequency response are conflicting with requirements to small physical dimensions and weight, so that a miniature accelerometer is bound to have a relatively low sensitivity. The housing of the miniature accelerometer has been made of titanium, and a high ratio of sensitivity to weight has been obtained without sacrificing any of the more important qualities of the accelerometer.

The total weight of the Miniature Accelerometer Type 4336 is 2 grams (o.07 oz.). Its main dimensions are given in Fig. 1.2. The weight is given without cable as it is difficult to predict how much the cable will add to the weight of the accelerometer. However the plug has been designed to give a very small extra mass and very reliable contact, and is situated very close to the mounting surface in order to allow the cable to be fixed to the mounting surface as close to the accelerometer as possible. This will ensure the most reliable operation. Furthermore two types of cable are included. The soft type should be used at temperatures up to 100°C (212°F) and the stiffer teflon cable at higher temperatures. For very critical work where the cable cannot be mounted directly onto the vibrating surface close to the accelerometer we recommend to remove the outer coating of the cable from about 10 mm from the plug and over as long a part as necessary. See Fig. 1.3. The sleeve is easily removed by a sharp razor-blade. Avoid however to cut down into underlying braided shield.

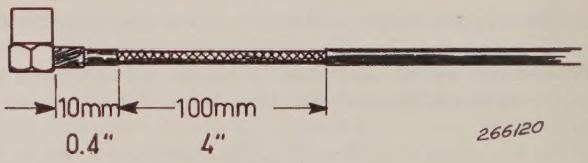


Fig. 1.3. Removal of outer cable insulation to reduce weight and stiffness.

Environmental Sensitivity.

Accelerometers are often used to measure vibration in the field or on specimens subjected to severe environmental tests. It is therefore important that their sensitivity to environmental changes is as small as possible. The factors that may influence accelerometer performance are primarily temperature, humidity and rapidly varying ambient pressure (Sound). The temperature effect is to reduce the voltage sensitivity of the accelerometer at higher temperature, but if the accelerometer has undergone a suitable temperature cycling process in the production stages, the sensitivity will revert to its normal value when the temperature is brought back to normal again. Beyond a certain temperature (the Curie point) the piezoelectric element is permanently damaged.

The Brüel & Kjær accelerometer Type 4336 is designed to be used for temperatures up to 260°C (500°F) without cooling. The sensitivity will be slightly reduced at the higher temperatures, but the necessary heat cycling process has been carried out, so that no permanent change will take place.

It should be noted that great care has been taken to use materials which will withstand high temperatures. The thermal coefficient of expansion of insulating material and metal parts are carefully matched in order to maintain humidity sealing.

It is, however, very difficult to guarantee a perfect seal for immersion in water when the accelerometers have been exposed to the high temperature limit. Therefore accelerometers which are to be used in liquids should not be exposed to more than 150°C for long periods of time.

The accelerometers are brought up to 250°C and left to cool down to about 50°C several times during production and calibration until performance is stable.

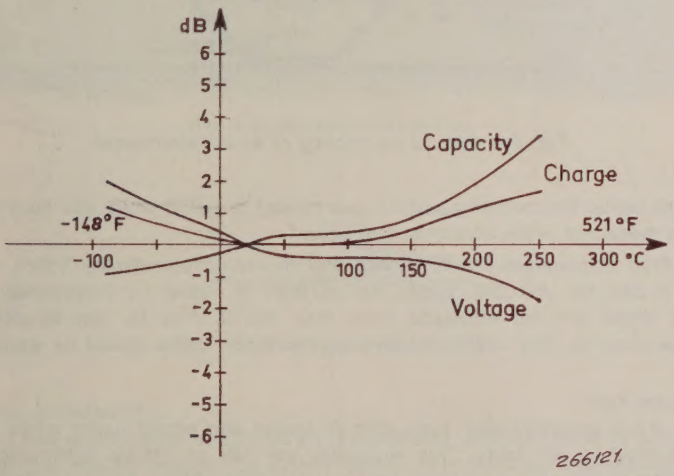


Fig. 1.4. Typical performance characteristics for the accelerometers in the temperature range –100 to +260°C.

Tests have also been conducted in order to find the influence of low temperatures on accelerometer performance. The voltage sensitivity increases steadily down to some –100°C and then levels out, while the capacity undergoes a gradual decrease with decreasing temperature. The charge sensitivity is practically constant.

Typical performance characteristics are given in Fig. 1.4 for the temperature range –100 to +260°C (–150 to +500°F).

Cooling.

When the accelerometers are fixed on surfaces with temperatures exceeding 250°C it is possible to reduce the temperature of the accelerometer base by inserting a cooling plate between the base and the measuring surface.

When a mica washer such as the one included in the Accelerometer 4316 is used between the mounting surface and the cooling plate, experience has shown that temperatures up to 350–400°C may be measured on the mounting surface with less than 250°C in the accelerometer base.

A stream of air passing over the cooling plate considerably aids the cooling process. The set-up shown in Fig. 1.5 has been tested in the laboratory.

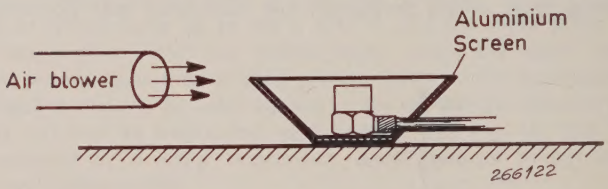


Fig. 1.5. Forced air cooling of an accelerometer.

In this set-up the mounting surface mas heated to 450°C while less than 200°C were measured in the accelerometer base.

For high temperature measurements one should always employ Teflon cable, B & K part No. AO 0052. Cable No. AO 0051 is based on Polyethylene and PVC which will not withstand more than 100°C. Also for low temperature measurements, from –40°C downwards, the Teflon cable should be employed.

Vacuum Test.

The B & K accelerometer Type 4336 is sealed and tested under water in an evacuated jar for leaks. This eliminates the risk of inferior performance in moist atmospheres or environmental test chambers where heavy condensation may take place.

A photograph of the test set-up is shown in Fig. 1.6. The smallest leaks show up immediately as bubbles rising to the surface.

When the accelerometers are used for measurements in liquids or in very moist environments it is necessary to seal the cable entry, as shown in Fig. 1.7. A good sealant for the cable entry is for example Dow Corning Silastic RTV 731 (room temperature vulcanizing silicon rubber) or General Electric equivalent. These sealants show excellent performance for a wide temperature range (–100 to +500°F).

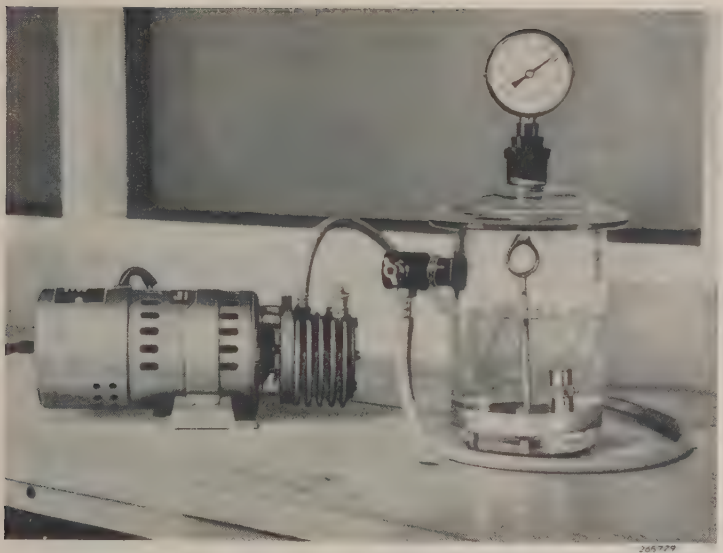


Fig. 1.6. Vacuum test set-up.

Fig. 1.7. Sealing of cable entry.

Acoustical Sensitivity.

Effects due to acoustical excitation are unavoidable with piezoelectric accelrometers, but may be reduced by careful design. The B & K accelerometers are of a rigid, mechanically isolated construction and pressure variations in the air will have little effect on the force exerted on the piezoelectric element. One may generally assume that the vibrations induced in the vibrating specimen will give rise to a much higher acceleration signal than the direct acoustical excitation of the accelerometer itself. In cases where very low accelerations are to be measured in an intense acoustic field, however, care must be exercised in order to obtain correct results. Typical acoustic sensitivity for the accelerometers has been measured and found to be less than o.5 μV/μbar, i.e. less than o.5 μV for 74 dB sound pressure level. At 140 dB sound pressure level the output is less than 1 mV.

Magnetic Sensitivity.
The magnetic sensitivity has been found to be less than 1 μV/Gauss for the least favorable orientation of the accelerometer in the magnetic field.

Polarity.
The polarity of the accelerometers is such that an acceleration directed from the mounting surface into the body of the accelerometer results in a positive e.m.f. on the centre conductor of the output terminals.

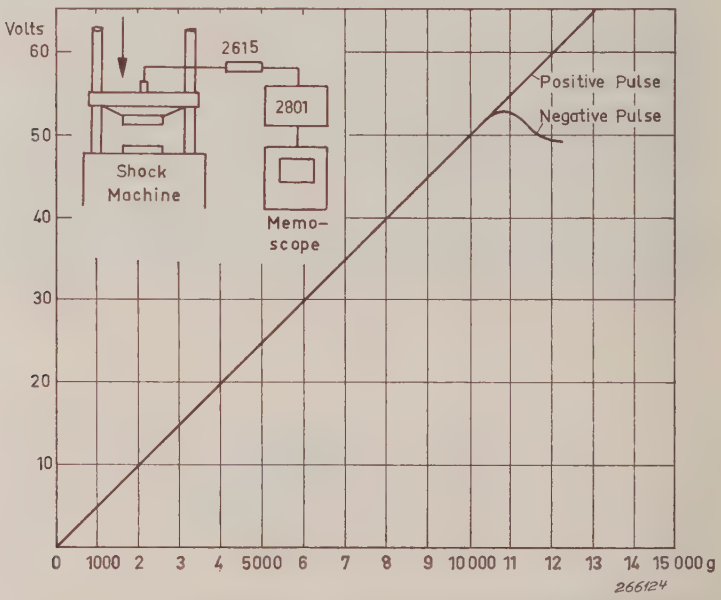


Fig. 1.8. Part of shock test machine and typical output versus shock amplitude plot.

Shock Performance.
In general the accelerometers will withstand shocks higher than 16ooo g in the positive direction, however, the mass is pressed against the ceramic with a certain force. This force determines the upper limit to which the accelerometer output will increase linearly with increased shock amplitude in the negative direction. When this limit is reached the output will be clipped as seen from the typical curve shown in Fig. 1.8.

Effect of Mounting Torque.
The effect of mounting torque is less than 1 % change in sensitivity up to 5ooo Hz for 2–20 kgcm (2 to 16 lb-in) mounting torque.

Long Term Stability.

A prime goal during design and manufacture has been to achieve maximum stability under severe environmental conditions. However, when an accelerometer is used for measurement under severe conditions of shock and heat, one should not rely on this as a primary standard. It would be advisable to recalibrate such an accelerometer at relatively short intervals of time.

A calibration vs. time history is closely followed for a number of representative units taken from production lots and they show less than 2 % change per year.

Piezoelectric Materials.

The quality of piezoelectric accelerometers depends largely upon the performance of the material used for the sensing elements. Monocrystalline materials such as quartz and Rochelle salt, have been used in the past, but are now superseded by polycrystalline, artificially polarized ceramics like barium titanate, lead zirconium titanate, lead metaniobate or similar materials. Large variations in electrical and mechanical properties are obtained by small changes in composition, and most manufacturers are continuously investigating and improving their compositions in order to make them more suitable for their particular purposes.

The most important factors for general purpose accelerometers are Curie point, sensitivity, temperature stability, capacity, resistance and time stability. Unfortunately some of these are conflicting, high sensitivity for example, has often to be sacrified for good time or temperature stability.

In the table below are given some properties of commonly used ceramics as given by their manufacturers. The Curie point is the temperature at which the

Manufacturer and Trade Name	Curie point °C	Piezoelectric Constant 10^{-12} Coul./Newt.	Dielectric Constant (Rel. Perm.)
Clevite Ceramic "B"	115	149	1300
Clevite PZT 4	325	285	1475
Quartz & Silice P 1-60	351	400	1500
Plessev Casonic Grade 3	120	83	1000
Quartz	300	2	4
B & K (1966)	350	300	1500

ceramic changes its crystal structure and looses its polarization, the piezoelectric constant indicates the sensitivity, and the dielectric constant indicates the capacity for a given shape and size. Trade names are used as the true composition of the ceramic is usually not disclosed by the manufacturer.

Natural Resonance Frequencies.

The natural resonance frequency of an accelerometer is not fixed. It depends not only upon the mass and stiffness of the accelerometer but also upon the mass (and stiffness) of the object on which it is mounted.

Some confusion persists as to what is the natural frequency and different definitions are seen.

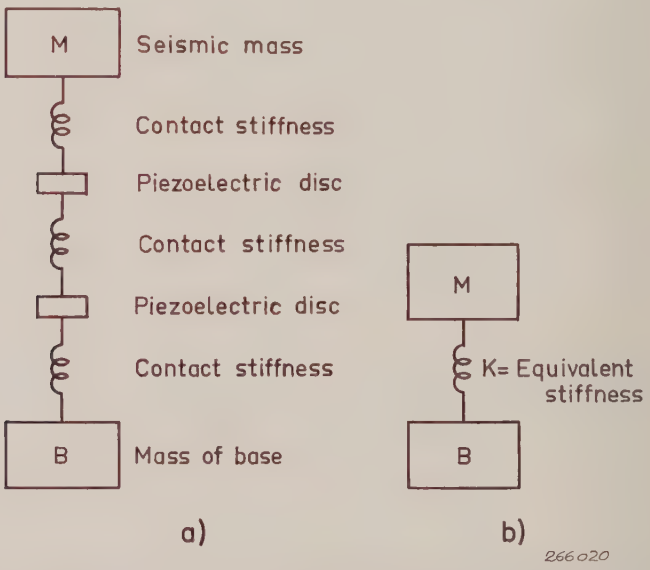


Fig. 1.9 a. Schematic drawing of accelerometer as a dynamic system.
b. Simplified system.

The situation is best illustrated with a drawing. Fig. 1.9a shows a schematic drawing of an accelerometer which consists of several masses and springs connected in series. These springs are representations of the contact stiffness between the various parts of the accelerometer.

This mechanical system can be further simplified into that of Fig. 1.9b. Here M is the seismic mass resting on the piezoelectric element, B is the mass of

the accelerometer base and housing. K is the equivalent stiffness of the system between M and B. The natural frequency of such a system is equal to

$$f_0 = f_M \sqrt{1 + \frac{B}{M}}$$

where f_M is the natural resonance frequency of the mass M upon the spring of stiffness K.

Now two resonance frequencies are easily thought of:

1. The *free hanging resonance frequency*, i.e. the resonance frequency obtained with the system freely suspended in air.
   This resonance frequency is entirely dependent upon the ratio of M and B, and it is seen that making the base B very light the resonance frequency may be very high. This resonance frequency is therefore of no practical value, in fact the higher it is, compared with the mounted resonance frequency defined below, the poorer is the mechanical construction of the transducer. (A thin base may cause bending of the piezoelectric due to strain from the mechanical part on which the vibration is measured).

2. The *mounted resonance frequency* with the accelerometer firmly fixed to a structure of infinite stiffness and mass.
   This results in a value for B of infinity and the resonance frequency is equal to f_M which is the natural resonance frequency of the mass M on the spring of stiffness K.
   This resonance frequency is of great practical value as it is approximately the one obtained when the accelerometer is mounted on a structure which is heavy compared with the accelerometer mass.

Unfortunately it is difficult to measure the mounted resonance frequency as defined above, since an infinitely heavy mass is hard to bring into motion.

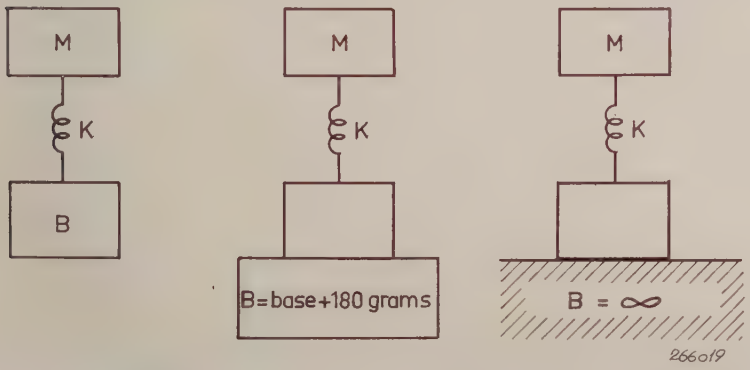


Fig. 1.10. Possible configurations for definition of natural resonance frequency.

A compromise has therefore to be made and there are standards which define the mounted resonance as that obtained with the accelerometer mounted on a one inch cube of steel (Brüel & Kjær use a steel block of weight 180 gram). Such a block is easily set into controlled motion at frequencies up to some 50 kHz.

This mounted resonance may be used directly as a basis for vibration measurements as long as the accelerometer seismic mass is much smaller than the mass of the calibration mounting block. The natural frequency obtained is practically identical with the mounted resonance frequency on an infinite mass. However when the accelerometer mass is large the natural frequency obtained will be too high, thus if B = 5 M we obtain

$$f_0 = f_M \sqrt{1 + 0.2} = 1.1 \; f_M$$

i.e. a value which is 10 % high.

For the miniature accelerometer the ratio of weights of the seismic mass to the weight of the base is about 1 : 1 and therefore the free hanging resonance will be about 1.5 times the mounted resonance and the resonance obtained on the 180 grams block of steel is 0.5 % higher than that which would be obtained on an infinite mass.

A small difference in resonance frequency is obtained by considering the damping present in the accelerometer. Thus *undamped natural frequency* is defined as the frequency at which the difference between the motion of the mass and base lags the motion of the base by a phase angle of 90°, whereas *damped natural frequency* is the frequency of decaying oscillations after an initial excitation. The difference is negligible for high Q piezoelectric accelerometers such as the ones manufactured by Brüel & Kjær.

The *undamped natural frequency* given on the accelerometer calibration charts is obtained with the accelerometer fixed firmly to a steel block of weight 180 grams.

2. Factory Calibration

Each individual accelerometer has before leaving the factory undergone a very thorough ageing, testing and calibration procedure to ensure the user of a high quality product. A typical calibration chart as supplied with the accelrometers is shown in Fig. 2.1.

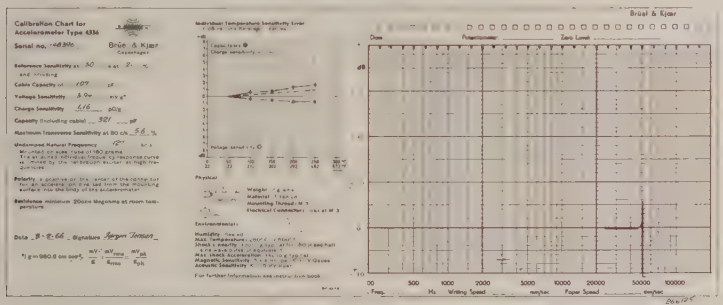


Fig. 2.1. A typical calibration chart.

Cable Capacity.

The capacitance of the accelerometers are given including the capacitance of the ordinary B & K connecting cable, so that when other cables are used, the change in cable capacitance must be taken into account, as this determines the effective sensitivity of the accelerometer. To find the capacitance of the accelerometer alone, deduct the cable capacitance given on the calibration chart. The standard length of cable included is 1.2 m (4 ft).

The capacity of the 1.2 m cable is around 105 pF (micromicrofarad) but the individual value is given on the calibration chart.

Voltage Sensitivity.

The voltage sensitivity of the accelerometers with connecting cable is determined at a frequency of 50 Hz and at room temperature (appr. 20°C).

Fig. 2.2 shows the instrumentation employed.

The accelerometers are calibrated at 50 Hz, the frequency being monitored by a crystal controlled electronic counter, and the periodic time of the vibration is kept within 200oo0 ± 100 μsec. Thus the frequency accuracy is ± o.05 %. The shaker providing the mechanical excitation is mounted on a large concrete

block which is supported by steel springs, giving the whole assembly a natural resonance frequency of about 1 Hz. This ensures isolation from background vibration.

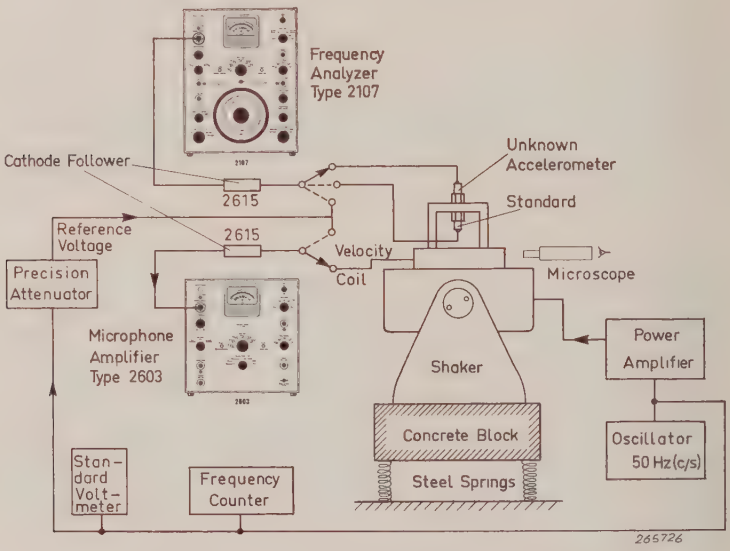


Fig. 2.2. Set-up used for calibration of absolute sensitivity of the accelerometers.

The calibration of all units is achieved by comparison between a standard accelerometer and the unknown in a back to back mounting as shown in Fig. 2.2. The standard is frequently checked with a microscope observing the displacement directly, with an accuracy of ± 1 %.

The distortion in actual vibration units is kept below 2 % and max. influence on peak to peak amplitude below o.5 %.

The output from the accelerometer is measured with a B & K Frequency Analyzer set to 50 Hz and calibrated with a reference voltage of exactly the same frequency as the signal to the shaker, giving a total voltage measuring accuracy of ± o.15 %.

The total accuracy on the sensitivity calibration of the accelerometers is thus better than ± 2 %.

The calibration vs. time history is closely followed for a number of representative units taken from production and they show less than 2 % change per year. Note that the calibration is valid for the accelerometer with its individual connecting cable, and remember to take any change of cable capacitance into account when different cables are employed.

Also the input capacity of the preamplifier must be taken into account. The influence of this capacity in the calibration set-up is eliminated with a substitution measurement. In practice the capacity will be less than 10 pF using a normal B & K amplifier and plug such as B & K Cathode Follower Type 2615, Source Follower 2616 or 4 pF in the case of Preamplifier 2623.
Note also the units employed in the calibration. The sensitivity is given in $mV/g = mV_{r.m.s.}/g_{r.m.s.} = mV_{peak}/g_{peak}$. If, for example, the sensitivity is required in $mV_{r.m.s.}/g_{peak}$ the sensitivity given should be multiplied by 0.707.

Charge Sensitivity.
This sensitivity is calculated from the voltage sensitivity and the equivalent capacitance of the accelerometer with normal connecting cable.
Charge sensitivity is expressed in pico-coulomb/g and is independent upon the capacitive loading on the accelerometer. It is determined by multiplying the voltage sensitivity with the total capacity used in the calibration, i.e. capacity of transducer and cable.

$$S_{charge} = S_{voltage} (C_a + C_c)$$

where C_a = accelerometer capacity and C_c = Cable capacity in nF.
Since the voltage sensitivity is given as mV/g the charge sensitivity will be in pico-coulomb/g.

Capacity.
The capacity of the accelerometer is given including the cable capacity as specified on the calibration sheet. Accelerometer capacity comes into the question when the low frequeny cut-off of the measuring system is computed, as it determines the effect of loading on the accelerometer.
The capacity is measured at 1ooo Hz in a capacitance bridge, comparing with a standard capacity equal to the nominal capacity of the accelerometers. Accuracy ± 0.5 %.

Transverse Sensitivity.
Transverse sensitivity is the maximum sensitivity to a transverse acceleration expressed in percent of the reference sensitivity in the intended measuring direction. It is primarily due to irregularities in the ceramics, and limitations in the mechanical coupling between ceramic and metal parts. Careful mechanical machining helps to minimize transverse sensitivity.
Transverse sensitivity can be regarded as a result of the axis of the accelerometer making a small angle with the direction of the maximum sensitivity as shown in Fig. 2.3.
Imaging the accelerometer placed in a rectangular coordinate system, as shown, the vector representing the maximum sensitivity can be resolved into two components: the main axis sensitivity which is the one called voltage or charge sensitivity on the calibration chart, and the transverse sensitivity given on the calibration chart as a percentage of the main axis sensitivity.

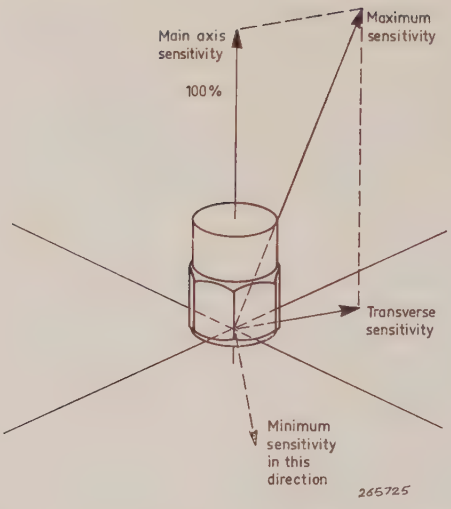


Fig. 2.3. Graphical illustration of transverse sensitivity.

The voltage obtained from an accelerometer is a product of the acceleration vector and the component of the sensitivity in the same direction, so that in a certain transverse direction, at right angles to both the main axis and the max. transverse sensitivity axis the accelerometer output will be minimum. In order to maintain a low transverse sensitivity the user should always mount the accelerometer on a flat, clean surface and keep the accelerometer mounting surface free from burrs and scratches. Also he should avoid very large shocks in the transverse direction, such as might be caused by dropping the accelerometer on the floor, and large temperature shocks.

If the accelerometer is properly handled and mounted, the transverse sensitivity will normally be below 10 % up to 5ooo Hz. Above 5ooo Hz it is very difficult to establish useful test facilities for transverse measurements. The type of mounting of the accelerometer will, however, undoubtedly set a limit to the good performance of the accelerometer in the transverse direction at a frequency somewhat lower than that for operation in the main direction.

The transverse sensitivity of the accelerometers is specified as being less than 8 % of the main axis sensitivity .However, the individual maximum transverse sensitivity is given on the calibration chart.

In the factory calibration the transverse sensitivity is measured at approximately 30 Hz on a rotating table whose motion sideways is more than 100 times larger than the motion in the vertical direction. See Fig. 2.4.

The accelerometer is first mounted with its main axis parallel to the direction of motion of the table and the deflection on the meter is adjusted to a

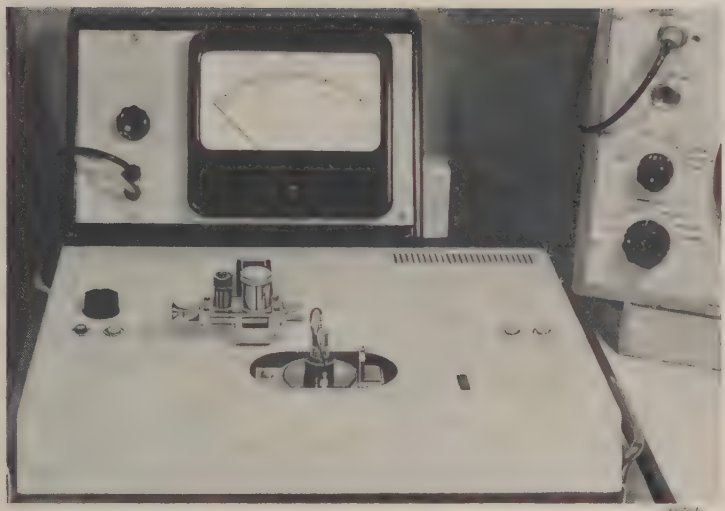


Fig. 2.4. Part of the arrangement for obtaining transverse sensitivity.

reference mark (100 %). Then the accelerometer is mounted with its main axis at right angles to the motion and the table is rotated slowly. The meter is set to indicate full scale deflection for 10 % transverse sensitivity and the maximum value is noted.
The factory calibration of transverse sensitivity is carried out after 24 hours of storage at room temperature.

Undamped Natural Frequency.
The undamped natural frequency is the frequency at which the motion of the seismic mass element lags 90° behind the motion of the accelerometer housing.
The damping ratio, which is the ratio between the actual damping of the accelerometer and the damping for which the system would be critically damped, is very low: in the order of o.02. Therefore the damped natural frequency, f_d, is nearly identical to the undamped natural frequency, f_u, since

$$f_d = f_u \sqrt{1 - o.02^2}$$

The undamped natural frequency is measured electrically by finding the lowest frequency at which the 90° phase shift occurs when an electrical signal is applied to the terminals in series with a 300 pF capacitor, and with the accelerometer mounted on a block of steel of weight 180 grammes.
The mounted resonance frequency is the frequency at which the sensitivity of the pick-up is a maximum when mounted on a stainless steel block of approx-

imately 180 grammes. As the mounted resonance given is obtained under actual operating conditions with the best possible contact between the accelerometer and the vibrating steel block this resonance can be taken as a practical upper limit. In practice the mounting will generally be less effective and a lower resonance frequency is obtained.

Frequency Response Curve.

An individual frequency response curve is supplied with each accelerometer. This is taken with the transducer mounted on a steel block of weight 180 grammes and with a plane mounting surface.

The instrumentation employed is similar to the set-up described in chapter "Calibration" and is based upon the B & K Calibration Exciter Type 4290.

In actual practice such a frequency response is to be expected from the accelerometer, provided the method of fixing to the vibrating specimen is satisfactory. It is generally accepted that the piezoelectric transducer may be used for frequencies up to about 1/3 of the resonance frequency shown by this curve for less than 1 dB error, or to 1/5 of the resonance frequency for less than 5 % error, but poor mounting methods will lower the resonance frequency and therefore also lower the upper frequency limit of the operating range.

The error at any frequency can be easily calculated from the formula for the relationship between the relative displacement of the mass spring system to the displacement of the base, viz.

$$\frac{\text{Relative Displacement of Mass-spring}}{\text{Displacement of base}} = \left| \frac{1}{1-\left(\frac{\omega}{\omega_0}\right)^2} \right|$$

where

$\omega = 2\pi \times$ forcing frequency and

$\omega_0 = 2\pi \times$ undamped natural frequency.

From this equation it may be seen that at 1/3 the resonance frequency the error will be 1 dB and at 1/5 the resonance frequency the error will be about o.5 dB.

Temperature Sensitivity.

Changes in accelerometer capacitance, charge sensitivity and voltage sensitivity with temperature are given for the range 20–250°C (70–480°F) with reference to the values given at room temperature.

These are individual values obtained while heating the accelerometers to the appropriate temperatures, reaching a steady temperature before measurement is taken.

The information is given in curve form so that interpolation can be readily performed.

When an accelerometer is used as a voltage generator, the transducer output in mV/g will depend upon the temperature of the piezoelectric and on the external loading. The calibration curve given is valid for the accelerometer with 1.2 m cable and thus for a capacitive loading of about 105 pF. Any change

in loading capacity will change the voltage sensitivity variation with temperature. It may therefore be possible to optimize the voltage sensitivity versus temperature characteristic.

The leakage resistance may also vary and alter the low frequency response. This effect is, however, negligible for the B & K accelerometers, since the leakage resistance is larger than 20000 Mohm for all temperatures in the operating range.

Charge amplifiers eliminate any influence of parallel capacity on the charge sensitivity versus temperature curve. Only series capacity should be considered, if present.

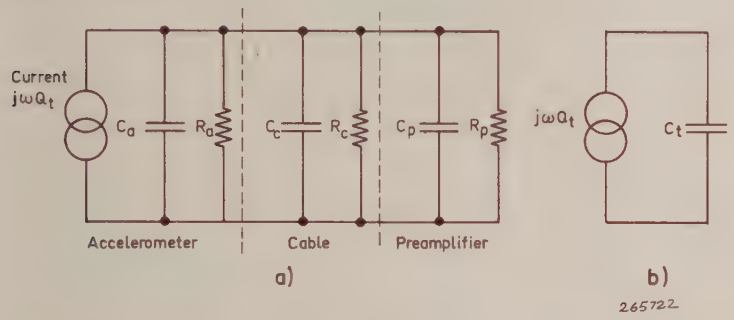


Fig. 2.5.
a) Equivalent circuit for accelerometer and preamplifier input.
b) The same circuit simplified for normal operating frequency range.

Considering the accelerometer as a charge generator it is easily seen from Fig. 2.5 that the voltage sensitivity at any temperature with any amount of cable capacity is

$$E_t = \frac{Q_t}{C_t}$$

where

E_t = voltage sensitivity at temperature t
Q_t = charge sensitivity at temperature t
C_t = total capacity in the circuit at temperature t

Now, the increase in charge sensitivity is given on the calibration chart in dB, so that knowing the charge sensitivity at room temperature the charge sensitivity at temperature t is easily found by using the conversion table for dB to ratio given in the appendix.

C_t is also easily found when the capacity external to the accelerometer is known. The increase in accelerometer capacity with temperature is given on the calibration chart, as well as the capacity at room temperature.

Therefore

$$Q_t = Q_o \times K_Q$$
$$C_t = C_a \times K_c + C_{ext} - C_c$$

where

Q_o = charge sensitivity at room temperature
K_Q = charge sensitivity factor
C_a = capacity of accelerometer plus associated cable (1.2 m) at room temperature
K_c = capacity factor
C_{ext} = total capacity external to the accelerometer (long cable plus preamplifier)
C_c = capacity of accelerometer cable used during factory calibration (1.2 m)

Then we have

$$E_t = \frac{Q_t}{C_t} = \frac{Q_o \times K_Q}{C_a \times K_c + C_{ext} - C_c}$$

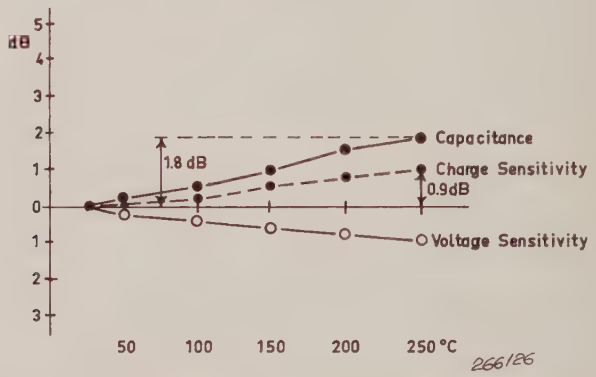


Fig. 2.6. Temperature sensitivity curves from the calibration chart on Fig. 2.1.

Example:
What is the voltage sensitivity of the accelerometer Type 4336, Serial No. 148396 (Fig. 2.1) at a temperature of 250°C and with a total external capacity (long cable plus preamplifier) of 1ooo pF.

Solution:
From the calibration chart we find

Q_o = 1.16 pCoulomb/g
K_q = 1 dB = 1.12
C_a = 321 pF
K_c = 1.6 dB = 1.2
C_c = 107 pF

Then the voltage sensitivity at 250°C

$$E_{250} = \frac{1.16 \times 1.12}{321 \times 1.2 + 1000 - 107} = 0.001016 \text{ V/g}$$

$$E_{250} = 1.02 \text{ mV/g}$$

Calibration Accuracy.

The accuracy of the above factory calibrations is better than ± 2 % for charge sensitivity, voltage sensitivity and capacity. The transverse sensitivity may change temporarily when the accelerometer is exposed to large shocks, especially sideways. Normally, however, it will return to the original value within the next 24 hours.

3. Mounting Methods

A proper mounting of the accelerometer to the specimen is of utmost importance when measurements are taken, especially at higher frequencies. The frequency response curve given on the calibration chart is for the best possible mounting of the accelerometer. (Screwed tightly with a steel stud onto a polished metal surface). When other methods are used the resonance frequency will generally be lower. How much lower will be determined by the mass of the accelerometer and the stiffness of the mounting.

Mounting Thread.

The mounting thread used for the Miniature Accelerometer Type 4336 is M3, both for fixing the accelerometer to the specimen and for the cable connection.

There are several methods available for fixing the B & K accelerometer to the specimen on which the vibration is to be measured. The following accessories for fixing purposes are included in the Accelerometer Set Type 4316:

Three M3 threaded studs and nuts
One cementing stud
Wax
One M3 screw tap
Allen key for steel studs.

Mounting of Accelerometer.

The possible ways for applying the accelerometer to the vibrating specimen are depicted in Fig. 3.1.

Type 1 mounting is the best solution frequency response wise, approaching a condition corresponding to the actual calibration curve supplied with the accelerometer. If the mounting surface is not quite smooth it is a good idea to apply a thin layer of silicon grease to the surface before screwing down the accelerometer. This increases the mounting stiffness.

Type 2 mounting is convenient when a cementing technique is desirable, while the possibility of removing the accelerometer from the vibrating surface from time to time is retained. This mounting can also be used to electrically isolate the accelerometer from the vibrating body. The stud is cemented onto the vibrating surface, possibly with a fine glass mesh in the cement to make sure that the stud is not touching the surface, and the accelerometer is screwed onto the threaded end of the stud.

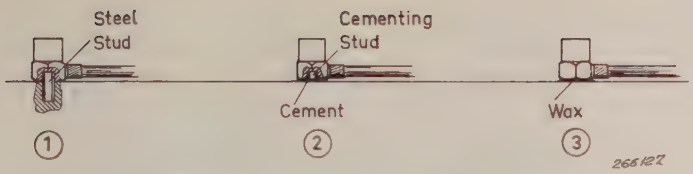


Fig. 3.1. Different ways of mounting the accelerometers.
1. With steel stud.
2. With cementing stud.
3. Accelerometer stuck on with wax.

Type 3 mounting employs a thin layer of wax for sticking the accelerometer onto the vibrating surface. The wax is delivered with the Accelerometer Set Type 4316. Due to the low mass of the accelerometer this mounting method may be used to quite high vibration levels, at ordinary room temperatures.
For minimum weight and optimum performance of the mounting one may also recommend the Eastman 910 cement, marketed by the Armstrong Industry, or Tixo K-1 manufactured by Tiox-Tinten und Klebstoffwerk G.m.b.H., Vienna. Dental cement and epoxy resins are also very useful, especially in connection with the cementing stud which is intended for use in applications where mounting by cementing techniques is preferred, while retaining the possibility of removing the accelerometer itself.
Soft setting glues or gum should be avoided because of decoupling and bad frequency response.

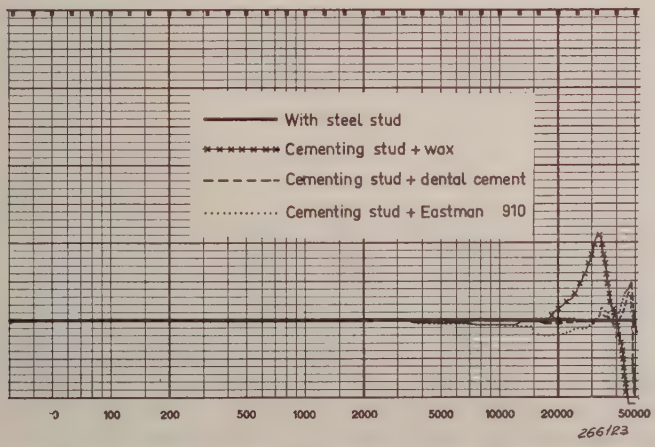


Fig. 3.2. Frequency response of an accelerometer for various types of mounting.

Fig. 3.2 shows some frequency response curves obtained for various types of mounting. The importance of the mounting method used should be obvious.

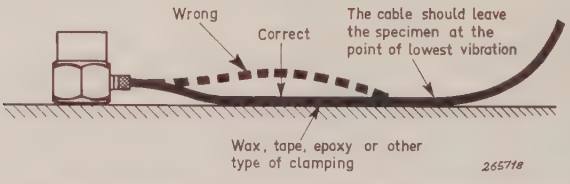

Wrong
Correct
The cable should leave the specimen at the point of lowest vibration
Wax, tape, epoxy or other type of clamping
265718

Fig. 3.3. Clamping of the cable to the vibrating specimen.

Mounting of Cable.

The connecting cable should always be given particular attention. Especially at lower frequencies it may give rise to noise voltages, due to bending or cable whip. The B & K accelerometer cable is designed and treated for noiseless operation, however, it is always good policy to clamp the cables as firmly as possible in order to avoid relative movement. See Fig. 3.3.

4. Measuring Systems

An accelerometer always works in connection with amplifiers and indicating instruments in order that the signal on the output terminals can be of some use to the operator.

A vibration measuring system usually consists of the following parts:

Accelerometer
Preamplifier
Integrating networks
Amplifier
Filter network
Indicating device.

In the Brüel & Kjær systems the amplifier, filter network and indicating device are often contained in one instrument. A block diagram of possible instrument combinations from the B & K program is given in Fig. 4.1.

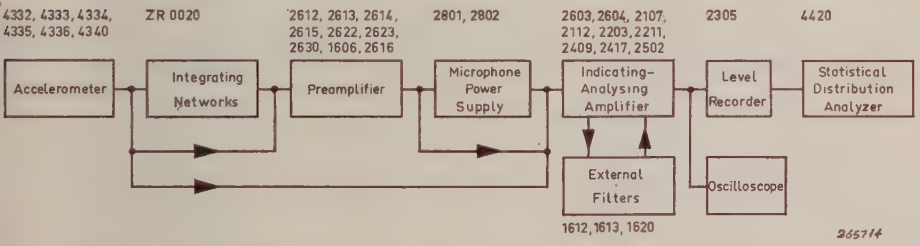


Fig. 4.1. Possible instrument combinations for vibration measurement and analysis.

Preamplifiers.

Preamplifiers are used for conversion of the rather weak transducer signal into a stronger signal which can be handled by the succeeding storage or read-out equipment. The signal from the piezo-electric accelerometer appears as a voltage across a capacitive impedance. The charge generated is proportional to the acceleration.

We have the choice of making the total capacity in the circuit as small as possible and thus obtain the highest possible voltage into the preamplifier, or to load the accelerometer so heavily with a shunt capacity that we have a system independent of small changes in cable capacity due to different lengths of cable. The first solution is called a voltage amplifier and the second a charge amplifier.

Voltage Preamplifiers.

When used as a voltage source the accelerometer must be loaded by an extremely high impedance in order to retain its sensitivity versus frequency characteristic. Capacitive loading reduces the sensitivity over the whole frequency range, while conductive loading reduces the sensitivity at low frequencies. This can be seen from the following:

The equivalent circuit of an accelerometer with external loading is drawn in Fig. 4.2.

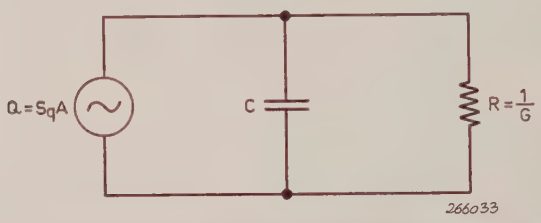


Fig. 4.2. Equivalent circuit of accelerometer and preamplifier.

- Q = charge induced across the accelerometer capacitive element
- S_q = charge sensitivity of the accelerometer (Coulomb/g)
- A = acceleration to which the accelerometer is subjected (g)
- C = total capacity in the circuit, including accelerometer, cable and preamplifier
- R = 1/G where G is the total conductance in the circuit, including accelerometer, cable and preamplifier.

Assuming a sinusoidal acceleration of angular frequency ω we have the current flowing in the circuit

$$I = j\omega Q$$

and the voltage output

$$E = \frac{I}{G + j\omega C} = \frac{j\omega Q}{G + j\omega C} \qquad (1)$$

This shows that when $G \ll j\omega C$ i.e. when the shunt resistance in the circuit is very high or at high frequencies the output voltage depends only upon the capacitive loading:

$$E = \frac{j\omega Q}{j\omega C} = \frac{Q}{C}$$

It is also seen that the output is directly proportional to 1/C. This must be taken into account when long accelerometer cables are employed.

From equation (1) it can also be seen that when $G \gg j\omega C$, i.e. for low frequencies or for low shunt resistance the output is frequency dependent:

$$E = \frac{j\omega Q}{G} = j\omega RQ$$

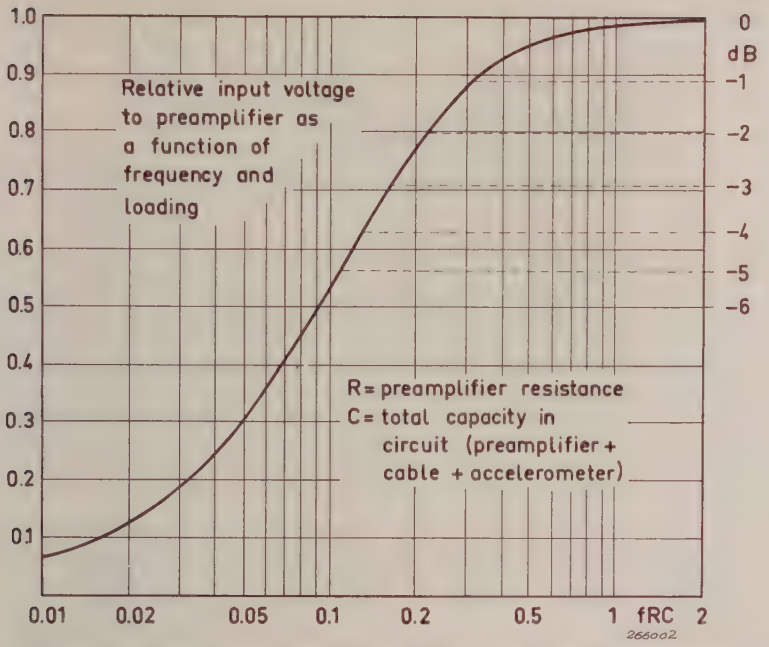


Fig. 4.3. Chart for finding required input impedance when accelerometer capacity and low frequency cut-off is given.

This means that the output falls off at the same rate as the frequency at the low frequency end. The corner frequency where the output is 3 dB down is where $|G| = |j\omega C|$

i.e. $$f_c = \frac{1}{2\pi RC}$$

where f_c is called the "cut-off frequency".

The internal resistance of the accelerometers is extremely high, always exceeding 20ooo Mohm at room temperature (~ 20°C). The resistance of the piezoelectric material is lower at high temperatures but usually still higher than 20ooo Mohm at 250°C. This large resistance gives a low frequency cut-off value of o.04 Hz for the accelerometer alone and thus makes measurement possible down to practically DC with specially designed amplifiers. Fig. 4.3 gives a chart for finding the required input resistance for a given lower limiting frequency and a given accelerometer capacity.

Example:

Find the required input impedance for a 1 dB cut-off at 1 Hz using an accelerometer with capacity 300 pF.

Solution:

A 1 dB cut-off is seen to give a value of about o.3 for fRC, i.e.

$$fRC = o.3$$

$$R = \frac{o.3}{fC} = \frac{o.3}{1 \times 300 \times 10^{-12}}$$

$$R = 1ooo \text{ Mohm}$$

The minimum acceptable input resistance of the preamplifier is 1ooo Mohm.

Cable Capacitance Sensitivity Correction.

The capacity of the cable connecting the accelerometer to the preamplifier will reduce the voltage sensitivity of the accelerometer. When the charge sensitivity of the accelerometer is given, as is the case with all B & K accelerometers, the easiest way to obtain the voltage sensitivity for any particular system is to divide the charge sensitivity by the total shunt capacity in the input circuit, i.e. accelerometer capacity, cable capacity and preamplifier input capacity. The capacity of the B & K accelerometer able is about 90 pF/m (27 pF/ft).

Example:

An accelerometer has a charge sensitivity of 1.5 pCoulomb/g and a capacity without cable of 200 pF. What is its voltage sensitivity with a connection cable of 4 m length? Preamplifier input capacity negligible.

Solution:

Cable capacity $4 \times 90 = 360$ pF

Total capacity $360 + 200 = 560$ pF

Voltage sensitivity $\frac{1.5}{560} = o.00268$ V/g $= 2.68$ mV/g

Charge Amplifiers.

The charge amplifier is gaining widespread acceptance mainly because of its simplicity of operation. It eliminates the effect of shunt capacity in the input circuit, so that the operator can work without attention to variable accelerometer cable lengths. The only information required is the charge sensitivity of the accelerometer.

An equivalent circuit diagram for accelerometer, cable and charge preamplifier is given in Fig. 4.4. By some calculation it is found that the output voltage is

$$E_o = \frac{Q}{\frac{C_a + C_c + C_i}{A} - C_f\left(1 - \frac{1}{A}\right)}$$

$$= \frac{QA}{C_a + C_c + C_i - C_f(A-1)}$$

which means that as long as $C_f(A-1) \gg C_a + C_c + C_i$ the output voltage is $-QA/C_f(A-1)$ independent upon cable capacity.

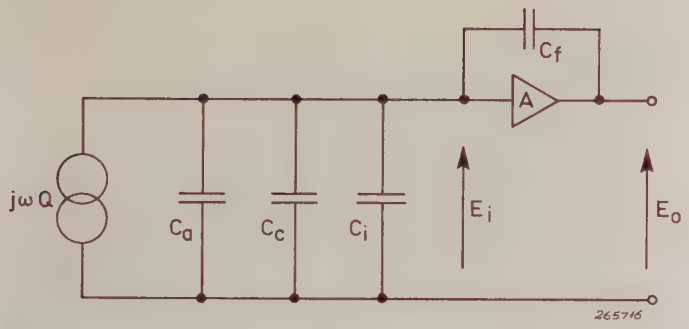


Fig. 4.4. Equivalent circuit diagram for accelerometer ,cable and charge amplifier.

The charge sensitivity is given on the calibration chart for the B & K accelerometers, but when this is not given it can easily be calculated by multiplying the voltage sensitivity with the total capacity (accelerometer plus cable) used in the calibration.

Note that the charge sensitivity of piezoelectric accelerometers does in general change with temperature. An individual charge sensitivity versus temperature curve is therefore supplied with each B & K accelerometer, covering the range 20–250°C (70–480°F).

Although the charge amplifier has advantages for certain applications, the following points should be considered:

The large amplification necessary for proper operation of the charge amplifier requires more components than what is necessary for a voltage amplifier. In practice this means higher costs and less reliable operation in severe environments.

More serious is the inferior rise time and recovery time obtained for most charge amplifiers. This is especially important for shock-measurements.

One of the arguments in favour of the charge amplifier is the possibility of using long cables between transducer and amplifier. This is, however, just as possible with voltage amplifier, if the gain is high enough to offset the loss in sensitivity, and in addition to this the voltage amplifier may have a superior signal to noise ratio. Charge amplifiers are therefore not recommended when low signals are to be measured.

One may conclude that voltage preamplifiers are to be preferred for the majority of applications. For special installations where long cables are used in different lengths, for example on vibration test sites or for measurements on large structures, the charge amplifier would be a natural choice.

B & K Preamplifiers.

Brüel & Kjær produce several types of preamplifier for use with the accelerometer in vibration measuring set-ups. These include:

1. Cathode followers (several types)
2. Preamplifier Type 1606
3. Preamplifier Type 2622
4. Battery Driven Preamplifier Type 2623
5. Battery Driven Preamplifier Type 2616

1. The microphone cathode followers fitted with input adaptors are excellent preamplifiers for the accelerometers when the measurement is one of acceleration only. Type 2615 is recommended. It has an input impedance of 200 Mohm in parallel with 3 pF which gives a low-frequency cut-off of approximately 2.5 Hz. The low-frequency cut-off of the system will therefore usually be determined by the following instruments. The cathode follower attenuation is approximately o.9 dB. The Integrator ZR 0020 may be screwed directly onto the 1" cathode followers, so that measurement of velocity and displacement may be carried out in addition to acceleration. See description below.

2. The Preamplifier Type 1606 is especially designed for vibration measurements. It contains integrating networks for measurement of velocity or displacement as well as acceleration. The gain is variable from 0 to about 38 dB and the input impedance is 200 Mohm in parallel with some 50 pF. The low-frequency limit is lower than 3 Hz for zero gain of the amplifier. A small shaker table on the preamplifier may be used to calibrate the whole vibration measuring set-up at a vibration level of 1 g peak (= 980.6 cm/sec^2 peak). The preamplifier is powered from the microphone input socket of one of the B & K microphone amplifiers or analyzers.

3. The Preamplifier Type 2622 is designed especially for use in vibration test set-ups in connection with other B & K vibration generators and control equipment, but may equally well be used on its own as an ordinary accelerometer preamplifier. It is a two-channel instrument which can be used either as a voltage or as a charge amplifier. Each channel has a three-decade attenuator which is set to the voltage or charge sensitivity of the accelerometer in use, within the range 10–100 mV/g or 10–100 pCoulomb/g. The output signal is then scaled to 10 mV/g.
   The lower limiting frequency can be chosen as 2–5–10 or 50 Hz. Apart from the two outputs there is a third output which can be automatically switched between the two channels, used for example for changing between two control accelerometers on a shaker table.

4. The Preamplifier Type 2623 is an impedance conversion device of an extremely small and rugged construction. See Fig. 4.5.
   An extremely high input impedance has been achieved through the use of a "field effect" transistor in the input circuit. The preamplifier is designed

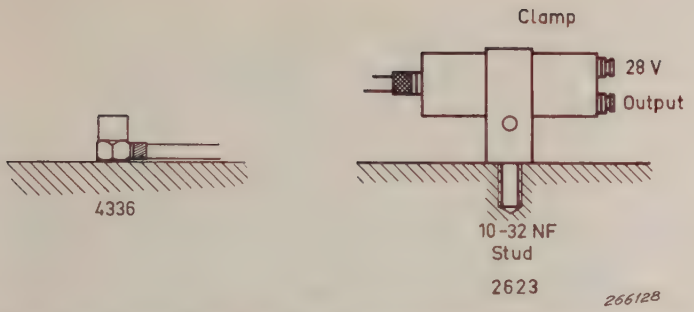


Fig. 4.5. The Preamplifier Type 2623 clamped near to the accelerometer.

to withstand severe environmental conditions and its sensitivity to vibration is extremely small.

Special features:

Input impedance:	Min. 2ooo Mohm at 25°C
	Min. 200 Mohm at 100°C
Output resistance:	40 ohm
Voltage gain:	0 ± o.05 dB
Frequency range:	o.5–500ooo Hz
Noise:	Max.15 μV, 2–40ooo Hz for 1ooo pF across input
Output voltage:	Max. 20 V peak-peak
Rise time:	$<$ 10 μsec.
Recovery time:	$<$ 50 μsec.
Dimensions:	45 mm × 14 mm dia.
	(1.77" × o.55" dia.)
Weight:	20.6 grammes

5. The Preamplifier Type 2616 is a battery driven three-stage transistorized impedance conversion device, suitable for use with high impedance transducers. Due to its small size it can be placed close to the accelerometer, thus minimizing sensitivity loss and noise from the connecting cable. See Fig. 4.6.
The preamplifier is battery driven from six built-in mercury cells or supplied from an external DC source, 6–35 volts.

Special features:

Input impedance:	1200 Mohm, 10 pF
Frequency range:	o.5–500ooo Hz
Dynamic range:	96.5 dB
Attenuation:	0 or 40 dB (fixed)
Amplification:	+2 to –20 dB (continuously variable)
Output voltage:	Max. 2.8 V peak-peak

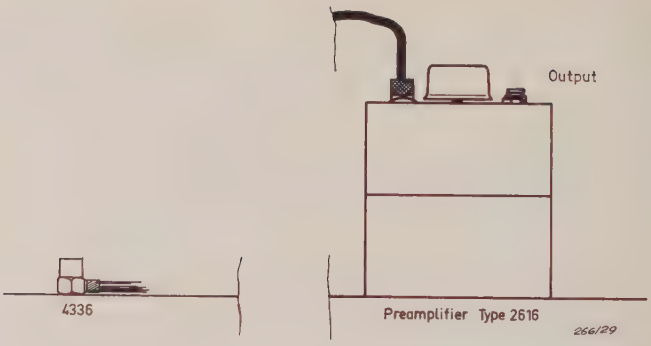


Fig. 4.6. The battery driven Preamplifier Type 2616.

Rise time:	< 10 μsec.
Recovery time:	< 50 μsec.

Integrating Networks.

Apart from the integrating networks contained in the Preamplifier Type 1606, Brüel & Kjær produce a separate unit called the Integrator ZR 0020.

The Integrator, containing two stages of integration, is designed for screwing directly onto a B & K Precision Sound Level Meter Type 2203, effectively converting this into a handy, portable vibration meter, capable of indicating levels of acceleration, velocity and displacement when an acceleration pick-up is employed as a vibration transducer. A slide rule is delivered with the Integrator which may be set to the acceleration pick-up sensitivity and used for direct conversion of dB-readings to units of vibration (metric and British). Accelerometer sensitivities from 10 to 1ooo mV/g are covered.

The components of the RC integrating networks have been chosen to give a low-frequency cut-off (–3 dB point) at about 5 Hz. This is sufficiently low, since the Precision Sound Level Meter itself has a low-frequency cut-off of about 5 Hz. The high-frequency limits are determined by the capacitive coupling between input and output and are about 15 kHz for velocity and 4 kHz for displacement measurements. These ranges are sufficiently large for the majority of applications.

It is also quite possible to use the Integrator with the B & K 1" Cathode Followers, whereby measurement and analysis of acceleration, velocity and displacement may be carried out with any of the B & K analysing/indicating instruments, i.e. 2107, 2112, 2603 or 2211.

Amplifiers and Indicating Instruments.

Brüel & Kjær produce a number of indicating amplifiers for use in vibration measuring set-ups. They include:

1. Microphone Amplifier Type 2603, 2604
2. Frequency Analyzer Type 2107
3. Audio-Frequency Spectrometer Type 2112
4. Sound Level Meter Type 2203
5. Vacuum Tube Voltmeter Type 2409
6. Vacuum Tube Voltmeter Type 2417
7. Level Recorder Type 2305.

1. **Microphone Amplifiers.** These are convenient to use both with cathode followers and with the preamplifiers. They measure overall vibration level, but are equipped with filter input and output sockets for operation with external filters in frequency analyzing set-ups. Frequency range 2603: Flat to within ± o.5 dB from 2 to 40ooo Hz. 2604: Flat to within ± o.5 dB from 10 to 200ooo Hz.

2. **Frequency Analyzer Type 2107.** This is a microphone amplifier similar to Type 2603 but with a frequency selective filter network built-in. In vibration measurements it is an excellent means for analyzing the frequency contents of the vibration signal. The analyzer is of the constant percentage bandwidth type and the bandwidth is selectable from about 6 % to 29 % of the tuned-in frequency. Using the 6 % bandwidth gives a clear indication of each frequency component of the vibration. An important advantage is the possibility for driving the frequency tuning mechanism from the Level Recorder Type 2305, to give automatic frequency spectrum analysis curves on precalibrated paper, when the two instruments are synchronized. Frequency range 2–40ooo Hz for overall measurements (frequency selective part switched out), 20–20ooo Hz for frequency analysis.

3. **Audio Frequency Spectrometer Type 2112.** This is again a microphone amplifier but with 1/3 and full octave, contiguous fixed filters built-in. The frequency range covered is 22 to 45ooo Hz when used selectively, 2 to 40ooo Hz when used for overall measurements. When used with the Level Recorder Type 2305 the filters may be switched automatically from the recorder and frequency spectra are recorded on preprinted, calibrated paper as either third octave or octave analysis.

4. **The Precision Sound Level Meter** has its own cathode follower built-in and may therefore be used with the accelerometer connected directly to its input terminals. Using the Integrator ZR 0020 described above the Precision Sound Level Meter is effectively converted into a light, portable vibration meter, for measurement of acceleration, velocity and displacement. The Octave Filter Set Type 1613 may be attached to the Sound Level Meter for a rough frequency analysis of the vibration. Frequency range for overall measurements: 20 to 20ooo Hz, and for octave analysis: 22.5 to 20ooo Hz.

5. **Vacuum Tube Voltmeter Type 2409.** This voltmeter is an excellent instrument for overall vibration measurements, used with for example the Micro-

phone Power Supply Type 2801 and a Cathode Follower Type 2615. The frequency characteristic of the voltmeter is flat to within ± o.2 dB from 2 to 200ooo Hz with true rms, peak or arithmetic average indication of the vibration signal. Using the Preamplifier Type 1606 one can measure velocity and displacement as well as acceleration level.

The Vacuum Tube Voltmeter may also be used with an input directly from the accelerometer, since the input impedance is as high as 10 Mohm in parallel with 20 pF. This means that vibration measurements may be carried out down to as low as 50 Hz employing the Voltmeter alone.

6. **Random Noise Voltmeter Type 2417.** This meter may be used as the above Type 2409, but the meter circuit employs selectable time-constants from o.3 to 100 seconds, which is used to obtain a stable reading when the vibration is irregular or "random" at low frequencies. An output socket is provided for use with the Level Recorder Type 2305. The output signal is DC, proportional to the rms level of the vibration, and the Level Recorder must be switched to DC operation. The frequency characteristic of the voltmeter is flat to within ± o.2 dB from 2 to 20ooo Hz.

7. **Level Recorder Type 2305.** All the amplifying-indicating instruments described above have an output terminal for feeding for example the B & K Level Recorder Type 2305. This provides a permanent written record of whatever is measured. as a function of time, or when the Recorder is coupled to a frequency analyzer, as a function of frequency. The Level Recorder is in itself a very versatile measuring instrument, capable of measuring rms, peak and average values of signals from 2 to 200ooo Hz or DC signals. Its dynamic range is variable from 10 dB to 75 dB, and the writing width is 50 or 100 mm.

   The Statistical Distribution Analyzer Type 4420 may be coupled to the Level Recorder to give a level/time distribution of the measured signal.

   The sampling frequency is variable from o.1 to 10 seconds and the width of the amplitude window is one tenth of the writing width of the Level Recorder.

   As the counters employed go up to 999,999, an analysis time of more than 24 hours is possible even with the highest sampling frequency.

Ground Loops.

In set-ups where ground loops are disturbing or where ground currents may be carried in the shield of the transducer cable, thus superimposing a noise voltage on the signal, one should first of all consider the use of isolated mounting. This may be obtained with a cementing technique, either using the cementing stud er cementing the accelerometer directly onto the vibrating surface. If one of these methods cannot be employed, a battery driven system may be the solution, or a battery driven preamplifier connected to AC driven equipment via a balancing transformer such as the B & K Type TI 0001. See Fig. 4.7.

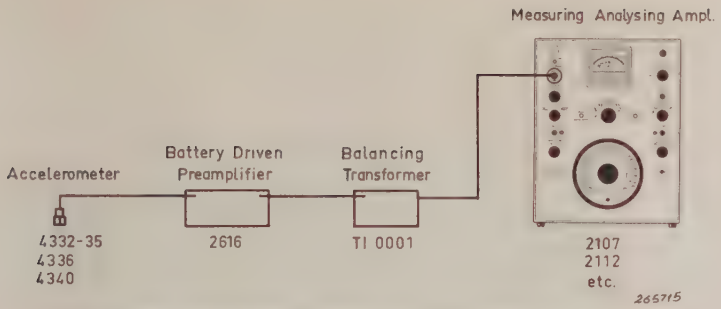


Fig. 4.7. Use of Balancing Transformer to eliminate ground loops.

5. Calibration

When absolute vibration level is measured it is necessary to know the absolute sensitivity versus frequency characteristic of the measuring instrumentation. As a rule piezoelectric accelerometers of careful design and manufacture are extremely stable, but after exposure to high temperature or shock environments it may be wise to recalibrate.

Equipment for relatively quick and simple calibration of vibration pick-ups is available from Brüel & Kjær. This consists of a small electrodynamic shaker Type 4290 with an accurately calibrated control accelerometer built in. Using the control accelerometer in a feedback loop with a B & K feedback controlled sweep oscillator the vibration of the shaker table is held constant in the frequency range 100 to 30ooo Hz, and when an accelerometer is fixed onto the shaker table its frequency response is easily measured, e.g. with a Level Recorder Type 2305, or point by point. A suitable set-up is shown in Fig. 5.1.

The Level Recorder is used for obtaining a permanent record of the frequency characteristic of the accelerometer. The absolute sensitivity of the accelerometer is found by comparing the output with the output from the built-in

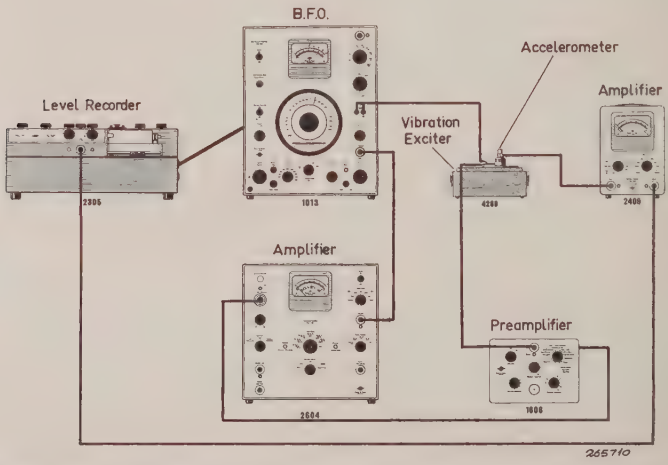


Fig. 5.1. Set-up suitable for the calibration of accelerometers. There are many possible alternatives to the various instruments shown.

calibrated control accelerometer. Since the shaker table itself is part of the control accelerometer, the vibration is exactly the same for the two accelerometers.

The comparison method gives an accuracy on the absolute calibration of better than ± 1 dB.

When higher accuracy is needed, or when it appears necessary to check the sensitivity of the control accelerometer, the same shaker may be used for reciprocity calibration. The procedure is described fully in the instruction manual for the Calibration Exciter Type 4290. The accuracy of this method is better than ± 0.5 dB with careful procedure.

An alternative method is to keep a "secondary standard" for reference calibration only. For this purpose any one of the accelerometers 4332 – 33 – 34 – 35 may be used. If this is kept for reference only and is not exposed to extreme mechanical shocks or temperatures, it will serve as a stable reference over a long period of time. Comparison between the reference and an unknown may easily be carried out on for example the 4290 shaker table. 2 % absolute accuracy is obtainable this way.

6. Instrument Combinations

The following are a few suggestions for instrument combinations which may be used in some common accelerometer applications. It is in no way suggested that this list covers more than just a fraction of the possibilities one might meet in practice. Nor does it necessarily give the one and only solution to the given problem. The selection of instrument combinations should always be given careful attention with due regard to frequency response, dynamic range, operating environment, accuracy, read-out device etc. It is hoped that the foregoing chapters will be of some assistance to the person responsible for such a selection.
Further information about the various B & K instruments is found in their respective Instruction and Application books.

Portable Instrumentation.
The Precision Sound Level Meter Type 2203 is an excellent amplifier for vibration measurements when portable instrumentation is required. Used with the Integrator ZR 0020 it can measure velocity and displacement in addition to acceleration. An octave filter set Type 1613 can be joined to the Precision Sound Level Meter for frequency analysis of the measured vibration quantity. See Fig. 6.1.
The frequency range of this system is from about 10 Hz to 20 kHz.

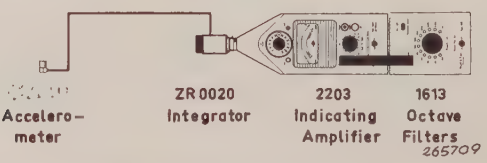


Fig. 6.1. Portable, battery driven instrumentation for measurement and analysis of vibration.

Such instrumentation is also well suited for collecting vibration data in the field with the aid of a portable tape recorder. Any desired vibration signal may then be recorded on the tape and brought back to the laboratory for subsequent analysis with more powerful instrumentation systems.

Frequency Analysis.
Frequency analysis of vibration may be carried out with the system depicted in Fig. 6.2. The frequency Analyzer Type 2107 has a selectable bandwidth

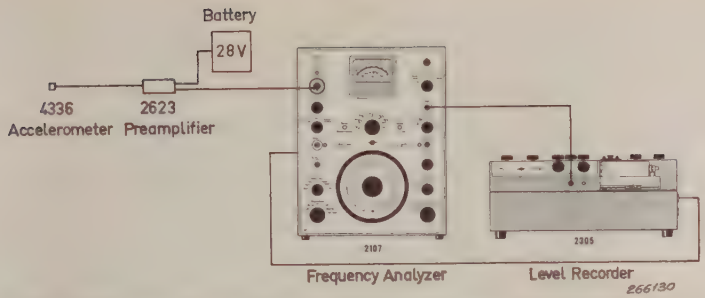


Fig. 6.2. Instrumentation suitable for frequency analysis of vibrations in the range 20–20000 Hz.

from about 6 % to 29 % and the centre frequency of the pass-band is continuously variable from 20 Hz to 20 kHz in six subranges. If a Level Recorder Type 2305 is used for driving the tuning mechanism of the Frequency Analyzer, the frequency spectrum can be recorded on preprinted, frequency and amplitude calibrated paper.
Overall acceleration can be measured in the range 2 Hz to 40 kHz.
The Frequency Analyzer may be substituted by a Spectrometer Type 2112 which has contiguous 1/3 and 1/1 octave filters in the range 22 Hz to 45 kHz.

Shocks and Transients.
Theoretical analysis of shock waveforms suggests that in order to measure a shock, a very wide frequency range is desirable. For a general pulse of duration T the system time constant, RC, should be at least 20 T for less than 5 % error. The system time constant is made up of the preamplifier input resistance, R, and the total capacity, C, in the input circuit, i.e. accelerometer, cable, and preamplifier input capacity all added in parallel.
The high frequency limit of the measuring system, including the accelerometer, should be at least 10/T Hz and the low frequency characteristics of the amplifiers should be flat down to 8/1000 T Hz. See B & K Technical Review No. 3-1966.

Phase Distortion.
In order to obtain an undistorted display it is also necessary that the various frequency components are phase delayed by an amount proportional to the frequency, i.e.

$$\varphi = k f$$

where φ is the phase distortion of the system at frequency f.
The system may be used for shock measurements when $k = 0$, i.e. no phase distortion, or when k is some positive or negative constant.
In shock measurements extremely high signal peaks may be encountered, and it is necessary to make absolutely certain that the dynamic capacity of the measuring system is sufficiently large.

High shock pulses, resulting in saturation of the amplifiers, may cause blocking of the amplifiers, and a certain "recovery time" will elapse before the next pulse can be measured correctly. This recovery time is to a certain extent dependent upon the low frequency cut-off of the amplifiers, so that the lower one's low frequency cut-off is, the more careful one must be not to overdrive the amplifiers. For pulse train measurements this is especially important.

With its very wide frequency range and large dynamic range, the Miniature Accelerometer is particularly well suited for shock measurements. Used together with one of the preamplifiers Type 2633 or 2616 the frequency range is from 0.5 Hz to 40 kHz, and the rise time and recovery time are 10 μsec and 50 μsec respectively. Rated conservatively such a system can be used for measuring shock pulses varying in length from 25 μsec to 16 msec. This covers most practical cases.

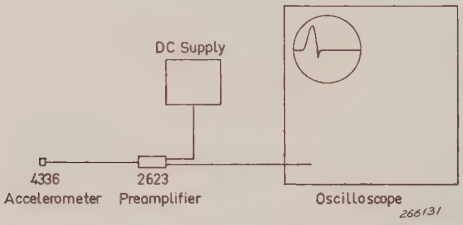


Fig. 6.3. Instrumentation suitable for shock measurements.

Another preamplifier well suited for shock measurements is the Cathode Follower Type 2615 connected as shown in Fig. 6.4.

This instrument combination gives a very large dynamic range and an excellent signal to noise ratio. The low-frequency cut-off is around 2.5 Hz (accelerometer capacity 300 pF, cathode follower input resistance 200 Mohm). As no phase-shift is introduced by the cathode follower the shock waveform is reproduced faithfully on the oscilloscope screen.

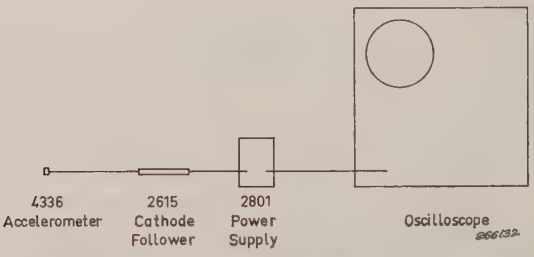


Fig. 6.4. Cathode Follower Type 2615 used for shock measurements.

Vibration Tests. Fig. 6.5 shows a typical arrangement for vibration testing of mechanical components. The component under test is mounted on an electrodynamic vibration exciter (shaker) which is fed from the Sine-Random Generator Type 1040 via a power amplifier. To maintain constant vibration level on the shaker table, independent of frequency, the output from the Sine Random Generator is regulated by the signal from an accelerometer (Type 4333) mounted on the table. The Preamplifier Type 2622 is used in the feedback loop to match the impedance of the accelerometer to that of the Vibration Meter Type 2501, and to standardize the output signal from the accelerometer to 10 mV/g.

Miniature accelerometers may be placed at various points of the tested structure for measurement of the response.

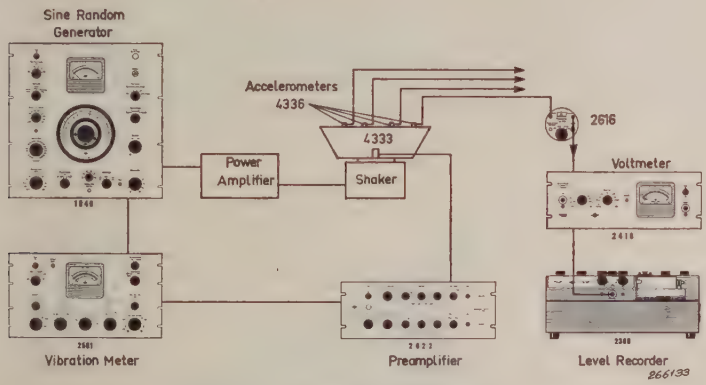


Fig. 6.5. Vibration test set-up.

Quality Control. In the last few years it has been realized that a vibration measuring system may be used for quality control of such items as electric motors, vacuum cleaners, refrigerator units etc. The Brüel & Kjær Noise Limit Indicator has been designed especially for production control of mass produced items with regard to their noise and vibration output. The instrument has two alternative inputs for B & K Cathode Followers or Preamplifiers Type 1606. 12 parallel output amplifiers may be fitted with plug-in filters, e.g. 1/3 or 1/1 octave filters, and a control panel with red lamps will indicate when the input signal level exceeds any preset value in each frequency band. On the basis of noise or vibration investigations on satisfactory production items, these limits may be set, and a quick production line control may be set up. In case of a fault in the item being tested, the vibration may be high in one or two particular frequency ranges. By looking at the frequency range in which

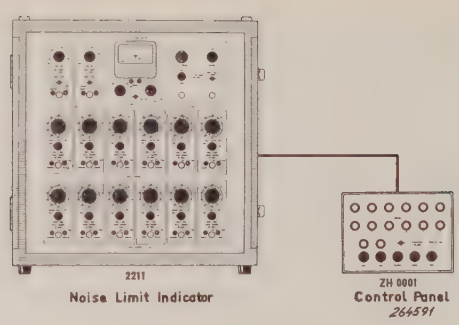


Fig. 6.6. The Noise Limit Indicator Type 2211.

the preset level is exceeded, it is often possible to tell straight away what the fault is, and it may be corrected without loss of time.
This method of quality control is covered more fully in B & K Technical Review No. 2-1963, "Quality Control by Noise Analysis". The Technical Review is mailed free of charge upon request.

7. What to Order

The Miniature Accelerometer Type 4336 is available as Accelerometer Set Type 4316 containing the following:

One accelerometer,
One low noise cable for ordinary temperatures,
One low noise cable for high temperatures,
Three threaded steel studs and nut (M3),
Cementing stud,
Wax,
Screw tap for 3 mm thread,
Allen key for steel studs,
Microplug to B & K plug adaptor,
Individual calibration chart.

See Fig. 7.1.

Fig. 7.1.

The Miniature Accelerometer is also available as Accelerometer Package Type 4356 containing

Five Miniature Accelerometers
Five Low noise cables for high temperatures
Five Low noise cables for ordinary temperatures
Five Steel studs, M3
Five Individual calibration charts

Any extra accessories must be ordered separately.

Accessories.

The following accessories are available for mounting of the accelerometers and the transistorized preamplifiers.

For **4336:**

AO 0051 1.2 m (4 ft.) of mininoise cable for operation to 100°C (212°F) fitted with miniature plugs. Individually calibrated capacitance value.

AO 0052 1.2 m (4 ft.) of mininoise cable for operation to 260°C (500°F) fitted with miniature plugs. Individually calibrated capacitance value.

For the transistorized preamplifiers Type **2616** and **2623:**

UA 0142 1 set of clamping magnet containing 5 permanent magnets UA 0070 with isolated mounting. Used for Preamplifier Type 2623.

UA 0129 Set of 20 miniature plugs JP 0012 with tools and instruction for mounting of the plugs on cable.

UA 0130 Set of 25 miniature plugs JP 0012.

AO 0037 1.2 m (4 ft.) of mininoise cable for operation to 100°C (212°F) fitted with miniature plugs. Individually calibrated.

AO 0038 1.2 m (4 ft.) of mininoise cable for operation to 260°C (500°F) fitted with miniature plugs. Individually calibrated.

AC 0010 Mininoise cable up to 600 ft. in one length.
90 pF/m or 30 pF/ft., for operation to 100°C (212°F).

AC 0005 Mininoise cable up to 600 ft. in one length.
90 pF/m or 30 pF/ft., for operation to 260°C (500°F).

JP 0028 Adaptor plug, microplug to B & K coaxial.

8. Conversion Charts, Tables etc.

The following table is given in order to facilitate the conversion from dB to a (voltage) ratio. It is used as follows:

Subtract a whole number of $n \times 20$ from the dB value to be converted which gives a positive remainder between 0 and 20. Look up the ratio in the table corresponding to the remainder. The value sought is then $10^n \times$ value from the table.

Example: Convert 65.3 dB re. 1 g into units of g.

$65.3 = (3) \times 20 + 5.3$.

5.3 gives from table 1.841. The g-value is then $10^3 \times 1.841 = 1841$ g.

With negative values the procedure is the same, e.g.:

Convert –31.8 dB re. 1 g into units of g.

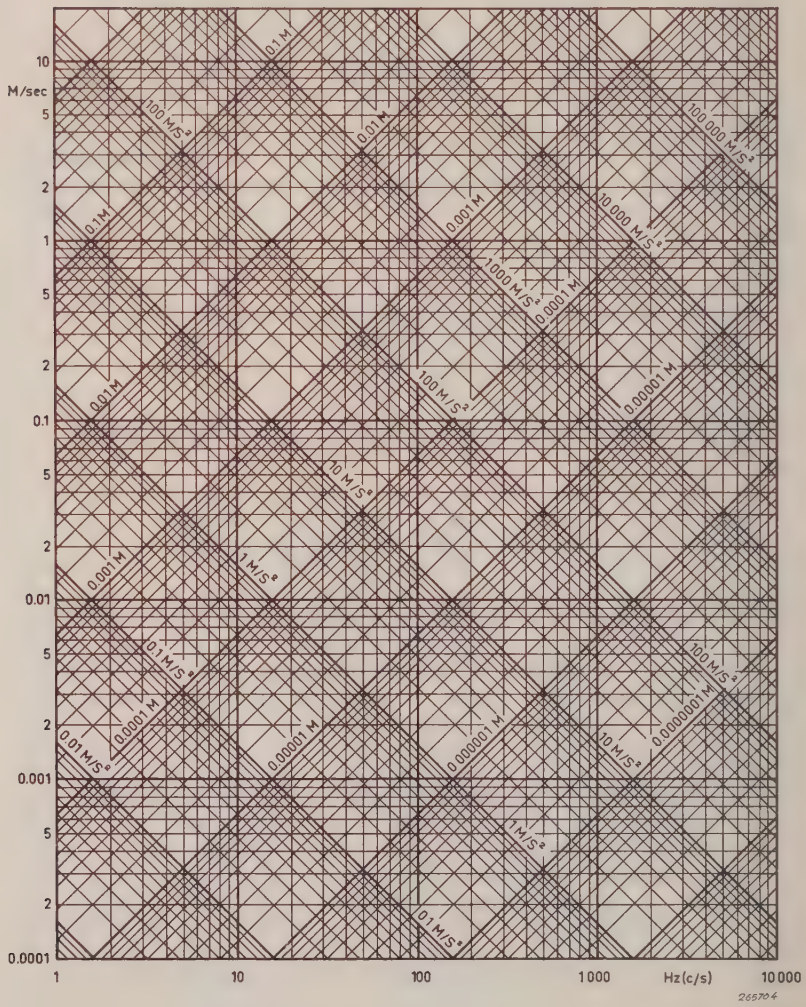
$-31.8 = (-2) \times 20 + 8.2$.

8.2 gives from table 2.570. The g-value is then $10^{-2} \times 2.570 = 0.02570$ g.

Table for Converting Decibels into (Voltage) Ratio.

dB	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0	1.000	1.012	1.023	1.035	1.047	1.059	1.072	1.084	1.096	1.109
1	1.122	1.135	1.148	1.161	1.175	1.189	1.202	1.216	1.230	1.245
2	1.259	1.274	1.288	1.303	1.318	1.334	1.349	1.365	1.380	1.396
3	1.413	1.429	1.445	1.462	1.479	1.496	1.514	1.531	1.549	1.567
4	1.585	1.603	1.622	1.641	1.660	1.679	1.698	1.718	1.738	1.758
5	1.778	1.799	1.820	1.841	1.862	1.884	1.905	1.928	1.950	1.972
6	1.995	2.018	2.042	2.065	2.089	2.113	2.138	2.163	2.188	2.213
7	2.239	2.265	2.291	2.317	2.344	2.371	2.399	2.427	2.455	2.483
8	2.512	2.541	2.570	2.600	2.630	2.661	2.692	2.723	2.754	2.786
9	2.818	2.851	2.884	2.917	2.951	2.985	3.020	3.055	3.090	3.126
10	3.162	3.199	3.236	3.273	3.311	3.350	3.388	3.428	3.467	3.508
11	3.548	3.589	3.631	3.673	3.715	3.758	3.802	3.846	3.890	3.936
12	3.981	4.027	4.074	4.121	4.169	4.217	4.266	4.315	4.365	4.416
13	4.467	4.519	4.571	4.624	4.677	4.732	4.786	4.842	4.898	4.955
14	5.012	5.070	5.129	5.188	5.248	5.309	5.370	5.433	5.495	5.559
15	5.623	5.689	5.754	5.821	5.888	5.957	6.026	6.095	6.166	6.237
16	6.310	6.383	6.457	6.531	6.607	6.683	6.761	6.839	6.918	6.998
17	7.079	7.161	7.244	7.328	7.413	7.499	7.586	7.674	7.762	7.852
18	7.943	8.035	8.128	8.222	8.318	8.414	8.511	8.610	8.710	8.810
19	8.913	9.016	9.120	9.226	9.333	9.441	9.550	9.661	9.772	9.886

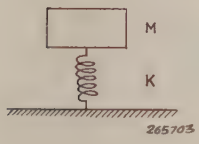
Frequency, Acceleration, Velocity, Displacement Nomograph. (RMS-values).



Temperature:

$$F = \frac{9}{5} C + 32 \qquad C = \frac{5}{9} (F - 32)$$

Single Degree of Freedom System.



M = mass (kg)
K = stiffness (Newt/m)

$\omega_o = \sqrt{\frac{M}{K}} = 2\pi \times$ resonance frequency

$\omega_o = \sqrt{\frac{g}{\Delta_{st}}}$ where Δ_{st} = static deflection of the mass.

For Single Frequency (Sinusoidal) Vibration.

Acceleration	Velocity	Displacement
$a \cos \omega t$	$\frac{1}{\omega} a \sin \omega t$	$-\frac{1}{\omega^2} a \cos \omega t$
$-\omega v \sin \omega t$	$v \cos \omega t$	$\frac{1}{\omega} v \sin \omega t$
$-\omega^2 d \cos \omega t$	$-\omega d \sin \omega t$	$d \cos \omega t$

RMS Values.

A	A/ω	A/ω^2
ωV	V	V/ω
$\omega^2 D$	ωD	D

Conversion of Length.

m	cm	mm	ft	in
1	100	1000	3.281	39.37
o.01	1	10	o.0328	o.3937
o.001	o.1	1	o.00328	o.03937
o.3048	30.48	304.8	1	12
o.0254	2.54	25.4	o.0833	1

Conversion of Acceleration.

g	m/sec^2	cm/sec^2	ft/sec^2	in/sec^2
1	9.81	981	32.2	386
o.102	1	100	3.281	39.37
o.00102	o.01	1	o.0328	o.3937
o.03109	o.3048	30.48	1	12
o.00259	o.0254	2.54	o.0833	1

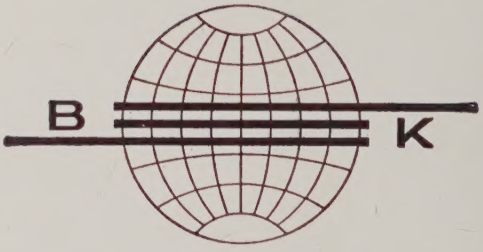
Conversion of Weight (Mass).

kg	gram	lbs.	oz.
1	1000	2.205	35.3
o.001	1	o.0022	o.0353
o.4536	453.6	1	16
o.02835	28.35	o.0625	1

9. Specifications

Accelerometer Type	*4336*
Contained in Accelerometer Set	4316
Contained in Accelerometer Package	4356
*Sensitivity (mV/g)	4–6
*Charge Sensitivity (pC/g)	1–2
*Free Resonance (kHz (kc/s))	125
*Mounted Resonance (Solid Steel) (kHz)	125
*Capacity Includ. Cable (pF)**	300
*Transverse Sensitivity (%)	$\angle$ 8
Max. Ambient Temperature (°C)	260
*Temperature Stability (dB/°C)	o.02
Lowest Leak Resist. at 20°C (MΩ) Typical value at 250°C (MΩ)	20ooo 20ooo
Magnetic Sensitivity (μV/Gauss)	1
Acoustic Sensitivity (μV/μbar)	$\angle$ o.5
Torque Sensitiv., 2–20 kgcm (%)	$\angle$ 1
Max. shock (g's)	14ooo
*Freq. Range (Hz (c/s)) 2 % 10 %	2–25ooo 2–40ooo
Type of Connection	Side
Height (mm)	9.2
Weight (grams)	2
Material of Base	Titanium
Provision for Water Cooling	No
Mounting thread	M3

* Individual values given on the calibration chart.
** With standard low-noise cable, 1.2 m (4 feet) long.



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